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Review Article

Image quality assessment of digital intraoral radiography — perception to caries diagnosis

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Summary The radiological diagnostic process is composed of the three major phases, psychophysical, psychological and nosological. An apparent improvement in image quality in the psychophysical phase does not necessarily imply an increased diagnostic performance. This may be true for the general diagnostic processes, but may not for the caries diagnosis, because psychophysical phase is of most significance in such special and relatively simplified task. In this article the processes to correlate perception to approximal caries diagnosis are reviewed using the Perceptibility Curve (PC) tests and Receiver Operating Characteristic (ROC) curve tests. The PC test was developed to represent the psychophysical property of the radiographic imaging system. Since physical properties are shown to be closely correlated with psychophysical properties, it is possible to theoretically calculate psychophysical properties of the radiographic systems from their physical properties. In a similar manner, observers' low contrast detectability in the psychophysical phase can be predicted from some physical parameters of the radiographic system. Observers' low contrast detectability is also correlated with the diagnostic performance obtained from ROC curve in the task of approximal caries diagnosis. Thus, considerably high correlation between psychophysical properties and diagnostic accuracy indicates close relationship between perception and approximal caries diagnosis. It implies that an improvement in the physical image quality leads to increased diagnostic performance to some extent in the approximal caries diagnosis.

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1. Introduction

The radiological diagnostic process is complicated and affected by many factors. A model for the radiologic process has been proposed by Blesser and Ozonoff [1]. They emphasize the importance of the perceptual dynamics in radiological interpretation as a first step toward the efficient improvement of the overall process. Their model predicates three major phases, psychophysical, psychological and nosological. They claim that an apparent improvement in image quality in the psychophysical phase does not necessarily imply an increased diagnostic performance since relationship between image quality and diagnostic utility is not straightforward. Their argument will hold true for the general diagnostic processes in radiology, but may not for the caries diagnosis, because psychophysical phase is of most significance in such special and relatively simplified task [2,3].

The psychophysical phase includes the X-ray recording system, display of the image, and processing by the human peripheral nervous system, and significantly influences the diagnostic accuracy [4]. Physical performance measures of radiographic imaging systems are the first important step in this psychophysical phase when comparing the imaging performance of competing systems, such as films and digital systems [5]. It is also known that physical properties of the radiographic systems correlate with observer performance to some extent [6]. The same relationship may hold true for perception and caries diagnosis. However, several intermediate processes are necessary to clarify the relationship between them.

In this article these processes to correlate perception to approximal caries diagnosis will be reviewed using the Perceptibility Curve (PC) tests and Receiver Operating Characteristic (ROC) curve tests.

2. Perception and image quality

2.1. Image quality and psychophysical property

The term "image quality" is often used to describe the psychophysical properties of the imaging system, but there is no criterion related to image quality [7]. Kundel [8] proposed three ways of assessing diagnostic image quality: by visual inspection of the image, measurement of diagnostic performance, and physical measurements made on the image or imaging system (Fig. 1). As the psychophysical phase in the radiological diagnostic process includes "image store", "image display", and "image perception" [9], psychophysical property shows the results of both physical measurements and visual inspection of the image in terms of the diagnostic image quality. Thus, sensitometric and the image transfer characteristics of the system represent psychophysical property of the system. Psychophysical property is a part of the overall image quality and eventually related to the diagnostic performance of the system.

2.2. Psychophysical property and Perceptibility Curve test

The Perceptibility Curve (PC) test was first developed by De Belder et al. [7] to represent the psychophysical property of the radiographic imaging system to make an image quality criterion with development of color radiographic systems, where the classical sensitometric evaluation was of little value. In this test, the number of contrast details that observers perceive is converted to the minimum perceptible radiation contrast over the whole exposure range. To construct a PC, a homogeneous block with small holes or disks of varying depths or thicknesses (Fig. 2) is exposed over the full exposure range of the system to be tested [10]. The mean reciprocal values over all observers of minimum perceptible radiation contrast, $\left|((\Delta \log E)_{\min})^{-1}\right|$, are then plotted as a function of $\log E$, where E denotes exposure. A total area under the curve represents the maximum contrast information content of the system (Fig. 3):

$$N = \int_{-\infty}^{+\infty} \frac{dN}{d\log E} d\log E \tag{1}$$

where N equals the total number of perceptible exposure differences in a radiograph, namely maximum contrast information content of the system. The range of the integral

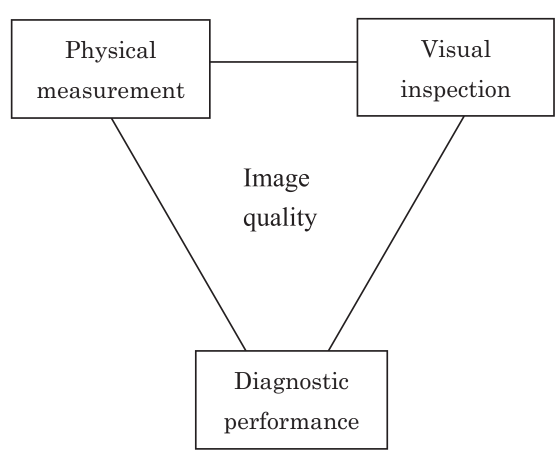

Figure 1 Three faces of diagnostic image quality proposed by Kundel HL.

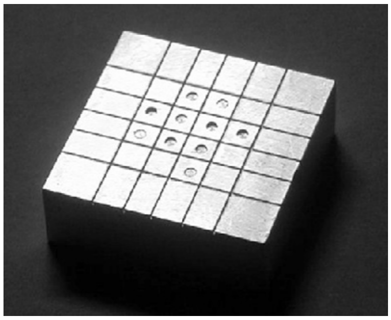

Figure 2 An example of the test object used for the PC test.

may be changed according to the exposure range used for radiographic interpretation. This equation can be expressed in the grayscale domain as following [10]:

$$N = \int_{-\infty}^{+\infty} \frac{dN}{d\log E} d\log E = \int_{0}^{G_{max}} ((\Delta G)_{min})^{-1} dG \qquad (2)$$

where $(\Delta G)_{min}$ is the minimum perceptible gray level difference in digital radiographs. Similarly, the range of the integral may be changed according to the grayscale range used for interpretation.

Psychophysical properties of different imaging systems, such as analogue and digital systems, can be quantitatively compared with the PCs [11]. Psychophysical properties of the digital intraoral systems have been shown to be superior to those of intraoral films. The main disadvantage of the PC test is that resolution of the imaging system cannot be evaluated with this method. With regard to resolution, digital systems are inferior to analogue films.

Simplified version of the PC has also been used to compare different imaging systems [12—14] or the effect of different viewing conditions [15]. This approach can be used to evaluate observer performance if the experimental conditions are exactly the same when the comparison is made. Psychophysical property cannot be evaluated with this simplified version since a simple change of the tube potential will easily affect the results [8].

As described above a test object used to construct PCs is usually a homogeneous block. An aluminum step phantom with small holes may be used to simulate the clinical radiation contrast range (Fig. 4) [16]. Using this phantom, differences in image quality could be quantitatively evaluated according to the number of visible holes in the radiographs [17]. In contrast to superior psychophysical properties of the digital systems, observer performance to detect low contrast details in digital systems is inferior to that in films in its original displayed image. Such inferior performance was improved by contrast enhancement, since inherent psychophysical properties of the digital systems are superior to those of films [17].

2.3. Human visual perception and perceptual linearlization

Human perception of all stimuli follows a non-linear relationship between the magnitude stimulus and the perceived one. As the psychophysical phase includes "image store", "image display", and "image perception", displayed images should be presented to the observer in the manner that each change in digital driving level of the display yields a perceptually equal step in perceived brightness by the human observer. This perceptual linearlization plays a significant role in medical image presentation [18] and a display function standard is proposed to minimize the mismatches between hard and soft copy presentation and to maintain standardized performance [19]. DICOM "grayscale standard display function" (GSDF) is proposed to be used by all imaging systems [20]. By exploiting the GSDF on all parts of the imaging chain, the same contrast impression on every monitor device can be obtained.

In addition to perceptual linearlization, compensation for the exponential attenuation function of the X-ray in the object is significant. Fig. 5 shows two radiographs of the step phantom obtained with film and with a digital intraoral system. It is clear that radiographic contrast obtained with the digital system is completely different from that obtained with film. Fig. 6 compares the contrast of the two systems in terms of luminance level. The contrast of the thick parts in the digital system is inferior to that of film. As it is known that the logarithmic response of films in conventional radiography approximately compensate for the exponential attenuation function, equal absorber thickness changes will results in approximately equal brightness changes [21]. As a majority of the digital systems adopt the linear gray-scale response to

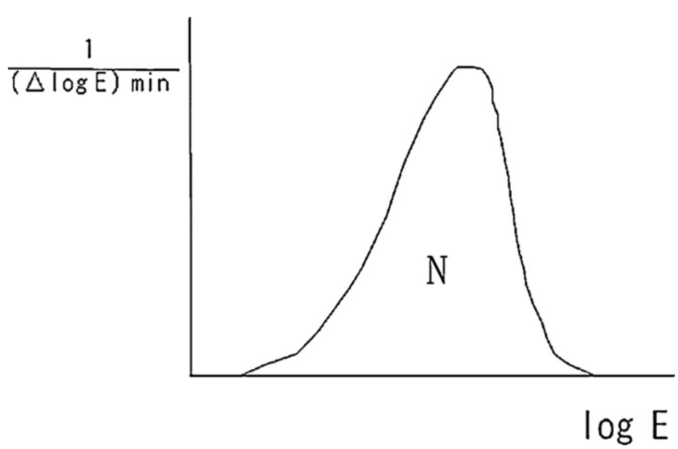

Figure 3 A typical PC for a given radiographic system. An area under the curve, *N*, indicates the maximum contrast information content of the system.

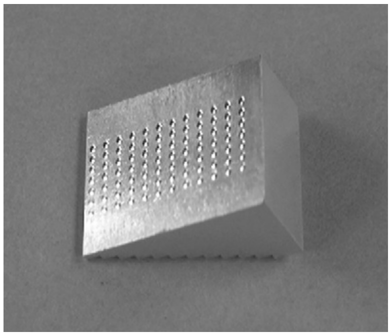

Figure 4 An example of aluminum step phantom covering most of the clinical exposure range.

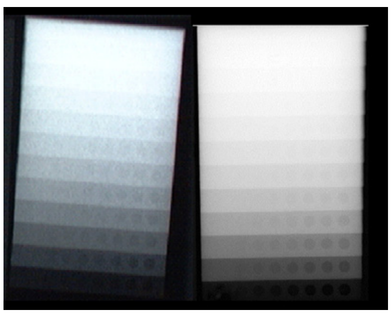

Figure 5 Radiographs obtained with Ekataspeed Plus film (left) and with Dixel digital intraoral radiographic system (right). Note the difference of radiographic contrast and noise.

radiation exposure, some kind of compensation will be needed for the exponential attenuation function of the X-ray to improve human visual perception with the digital systems [21]. A PC test has shown that appropriate correction for attenuation and visual response increases maximum contrast information content of the system [22].

3. Physical properties and observer performance

3.1. Physical properties and psychophysical properties

Standard measurement techniques exist to allow the quantification of the physical properties of the radiographic systems which affect image quality (resolution, contrast and noise) [5]. In addition to this, physical model for human contrast sensitivity has been proposed [23]. Using these methods it is possible to theoretically calculate psychophysical properties of the radiographic systems from their physical properties. De Belder also presented an expression to predict PCs that gives the probability that an average observer will perceive a certain exposure difference [7].

The following expression for digital radiography can be derived from the original definition for a PC:

$$\left|((\Delta \log E)_{\min})^{-1}\right| = \left|\frac{\gamma}{(\Delta G)_{\min}}\right| \tag{3}$$

where γ is the gradient of the dose response function of the imaging system. Using this equation, a simplified method to

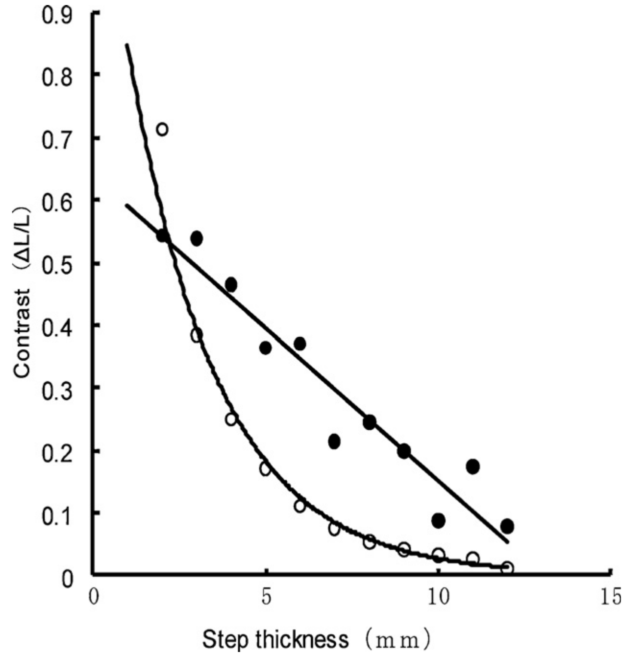

Figure 6 Comparison of the radiographic contrast of the film (closed circles) and the digital system (open circles) on the luminance basis. Approximation was made by linear function for the film and exponential for the digital system.

predict PCs of digital intraoral radiographic systems was developed [24]. γ can be simply calculated from the dose response function and $(\Delta G)_{\min}$ can be calculated using the physical model for human contrast sensitivity including the effects of internal and external noises. Since contrast and noise properties of the imaging system are included together with human contrast sensitivity function, psychophysical properties of the imaging system can be calculated by this equation. It clearly shows the close relationship between physical and psychophysical properties.

3.2. Physical properties and observers' low contrast detectability

Eqs. (2) and (3) imply that contrast information content can be calculated from some physical properties of the system and physical model for human contrast sensitivity [23]. Thus, the numbers of object details that the observers can perceive are calculated with regard to radiographs of the aluminum step phantom. Fig. 7 shows the correlation between calculated numbers of object details from digital radiographs and actual observer data. The correlation coefficient is remarkably high ($r = 0.98$). In addition, the inclination of the regression line is approximately 45° indicating that the calculated numbers of object details are very close to the actual observer performance [25]. This implies that observers' low contrast detectability can be predicted from some physical parameters of the radiographic system.

4. Perception to approximal caries diagnosis

Receiver Operating Characteristic (ROC) curve is considered to be the only scientific method to evaluate the effects of the

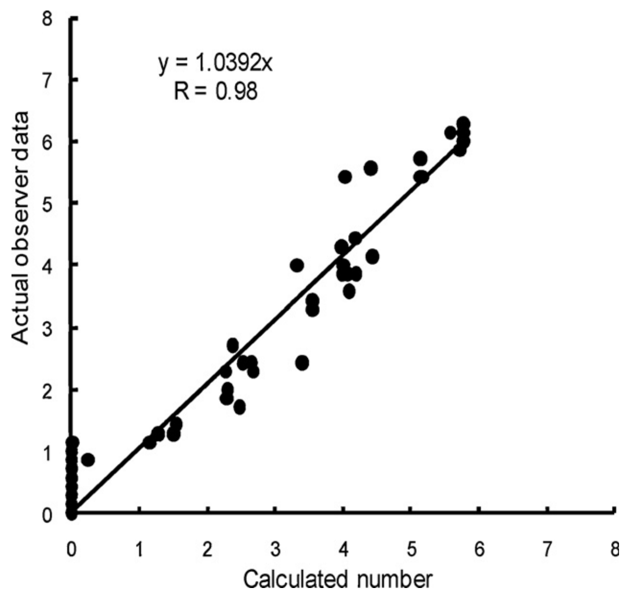

Figure 7 Correlation between calculated numbers of object details and actual observer data.

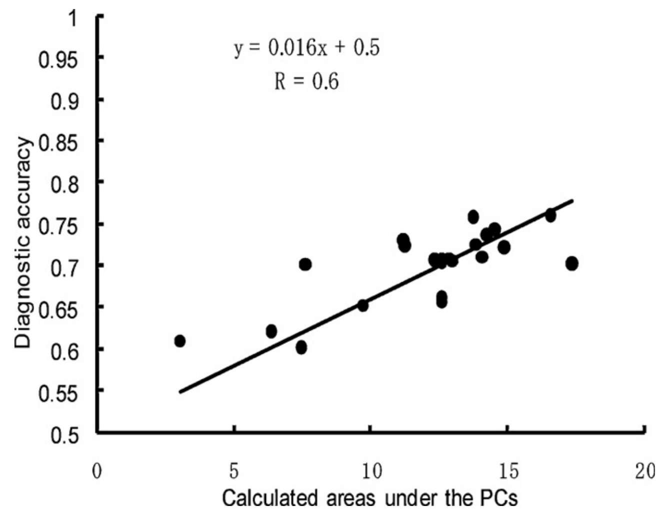

Figure 8 Relationship between the calculated areas under the PCs and diagnostic accuracy.

system performance on the diagnostic outcome [26]. ROC curve is based on the statistical decision theory and made by plotting the conditional probability of true positive responses by an observer in a detection experiment where signal is detected from noise, versus the conditional probability of false positive responses. The area under the ROC curve represents diagnostic accuracy in evaluation of radiographic systems. Decision criteria in radiographic caries diagnosis were constructed using ROC curve method [27]. Now ROC curve test is widely applied to evaluate system performance or to compare diagnostic performance of different systems [28—30]. Demerit of this ROC test is that it is time-consuming and elaborate.

One may notice similarity of N, maximum contrast information content obtained from the PC (see Eq. (1)) to the area under the ROC curve which represents image information content per observation. However, there is a fundamental difference between these two methods. PC test is just a detection task of the prepositioned signals and include no false positive responses, while ROC curve test includes both false and true positive responses. PC test only represents psychophysical properties of the radiographic system, while ROC curve test represents overall system performance including psychological and nosological phases. Therefore, PC test result may be a part of ROC curve test results. If we recognized the relationship between PC test and ROC curve test, experimental setting could be simplified, and the PC test results might be extrapolated to ROC curve test results.

As described in Section 1, radiological diagnostic process consists of three phases, and effects of psychological and nosological phases may be important in medical diagnostic tasks. In the radiological diagnosis for approximal caries, the location of the abnormality is confined to the proximal surfaces and diagnostic task is to detect presence of the abnormality and to evaluate the degree of abnormality, namely the depth of carious cavity. In this context, there is a possibility to clarify the relationship between PC test and ROC curve test in radiographic diagnostic task for approximal caries.

Li et al. reported that psychophysical properties can be improved by perceptual linearlization for attenuation and visual response using PC tests [22]. The same image processing method has been applied to the radiographs of the aluminum step phantom. Observer performance to detect low contrast details has been similarly improved [21]. This method has also significantly improved the diagnosis of approximal caries in digital radiographs [3]. A series of these results suggests the close relationship between psychophysical properties obtained from PC and diagnostic outcome obtained from ROC curve test results in the diagnosis of approximal caries.

In order to correlate psychophysical property to diagnostic accuracy, we have to determine the exposure range utilized for approximal caries diagnosis. According to the experimental result using the aluminum step phantom, exposure range used for the approximal caries diagnosis corresponded to five contiguous steps from 2 mm to 6 mm thickness [31]. Using this exposure range, contrast information content can be calculated from Eq. (1). Fig. 8 shows correlation between the calculated areas under the PCs and the actual diagnostic accuracy. The same samples were used for calculation as those in Yoshiura et al. [31]. It shows considerably high correlation between psychophysical properties and diagnostic accuracy in the diagnosis of approximal caries. Inclination of the regression line may change according to the nature of the caries samples, such as caries depth. Deeper caries samples will make the inclination steeper leading to higher diagnostic accuracy.

5. Conclusion

Although the radiological process in medical diagnostic tasks may be complicated, the radiological diagnostic process for approximal caries seems to be relatively simple. There is a clear correlation between psychophysical properties of the radiographic system and diagnostic accuracy obtained from it. It means that perception plays a significant role in the approximal caries diagnosis. It implies that an improvement in the physical image quality leads to increased diagnostic performance to some extent in the approximal caries diagnosis.

The relationship between the PC test and the ROC curve test may be similar to the relationship between mechanical defects and natural caries in the ROC curve test [32]. Some converting factor similar to the odds ratio in their study can be used to compare the results from those different methods.

In this article, other factors that may influence diagnostic performance in digital intraoral radiography, such as resolution or the diagnostic accuracy for alveolar bone resorption, are excluded. They must be included in evaluating the image quality of digital intraoral radiography on a clinical diagnostic task basis.

Conflict of interest

Nothing to declare.

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